Modeling Wind Wave Evolution from Deep to Shallow Water

Tim T. Janssen

Theiss Research, PO Box 1533, El Granada, CA 94018
t: 415 609 5359 e: ttjanssen@gmail.com

Thomas H. C. Herbers

Department of Oceanography, Code OC/He, Naval Postgraduate School
Monterey, California 93943
t: 831 656 2917; e: thcherbers@gmail.com

Gerbrant Ph. van Vledder

Department of Civil Engineering and Geosciences, Delft University of Technology
2600 GA Delft, The Netherlands
t: +1 31 15 2781953 ; f: +1 31 15 2784842 ; e: g.p.vanvledder@tudelft.nl

Award: N000141310055, N0001414WX20249, N000141010391

LONG-TERM GOALS

Ocean waves are an important aspect of upper ocean dynamics, in particular on shallow continental shelves and in coastal areas. The long-term objective of this work is to advance modeling capability in such coastal areas by improving model representations of effects associated with nonlinearity, medium variations, and dissipation.

OBJECTIVES

The specific objectives of the present work are 1) to develop and implement an efficient and scalable approximation for the nonlinear quadruplet source term, 2) to develop a generalized nonlinear source term that is accurate in water of arbitrary depth, 3) to develop improved nonlinear closure approximation for triad nonlinear interactions in shallow water, 4) to develop and implement a new stochastic model for coherent wave interference induced by varying depth and currents, and 5) improve representations of dissipation by wave breaking and wave-bottom interactions in shoaling waves.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Modeling Wind Wave Evolution from Deep to Shallow Water**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School (NPS),Department of Oceanography,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Modern, third-generation (3G) wave models are based on an action balance (or radiative transfer) equation, which describes the transport of wave energy (or action) through a slowly varying medium and time. In Lagrangian form (for convenience) this balance equation can be written as

$$\frac{dN(\mathbf{k})}{dt} = S_{in}(\mathbf{k}) + S_{ds}(\mathbf{k}) + S_{sc}(\mathbf{k}) + S_{nl}(\mathbf{k}) \qquad (1)$$

where $N(\mathbf{k})$ is the wave action at wavenumber vector $\mathbf{k}$ and t is time. The forcing terms on the right-hand side are referred to as source terms and account for the input of energy by the wind (S_{in}), spectral redistribution of energy through scattering by seafloor topography (S_{sc}) or through nonlinear wave-wave interactions (S_{nl}) , and dissipation of wave energy (S_{ds}) through e.g. breaking or bottom friction.

In this study we will develop and improve the source terms for nonlinear interactions S_{nl} and energy dissipation S_{ds}, to account for effects of finite depth and shallow water, and to ensure a consistent and smooth model representation of wave evolution from deep to shallow water.

Nonlinearity

We will develop theory and modeling capability to transport (nonlinear) cross-correlators through regions of variable depth. To allow modeling of wave propagation from deep to shallow water, we will modify the nonlinear source term to account for changes in relative water depth [Janssen *et al.* 2006], and develop an improved closure approximation for nearshore wave propagation [Janssen, 2006]. To allow for more efficient evaluation of nonlinear four-wave interactions in operational wave models, we develop a Lumped Quadruplet Approximation (LQA) by rewriting the exact WRT method to reduce the number of effective configurations by lumping contributions along the loci-integration.

Dissipation

We test wave dissipation in muddy environments by comparing model simulations with an operational wave model to recent field observations of waves propagating across a muddy seafloor for a range of wind and wave conditions.

Field data

We will analyze, prepare, and disseminate selected field experimental data sets, collected by the PI's and colleagues, to the project teams for the purpose of validation and calibration of new model developments. The data will be made available through a dedicated website.

WORK COMPLETED

Development of a Lumped Quadruplet Approximation (LQA)

A first step in the inter-comparison of exact methods has been carried out using the WRT method as implemented by Van Vledder (2006) and the RIAM method of Masuda (1980). The results of the inter-comparison were presented at the 13th International Workshop on Wave Forecasting and Hindcasting, Banff, Canada, (Van Vledder and Hashimoto, 2013). Results of Lavrenov's Gaussian Quadrature Method (see Lavrenov, 2001), as implemented by Gagnaire-Renou et al. (2010) are now being processed and added to the inter-comparison study. Moving forward, the recently introduced exact method of Onorato and Janssen (2013) and analytic solutions (Dungey and Hui, 1979) for narrow-peaked spectra, will be added to the comparison.

The LQA and the Generalized Multiple DIA have been implemented in subroutine form and included in the research wave model WAVETIME of Van Vledder. Since each approximation of the nonlinear source term will affect other source terms as well, the focus in the assessment of the new approximation is on the reproduction of integral model results, rather than the ability to represent the details of the nonlinear transfer rate for an arbitrary spectrum. The LQA and the GMD are now being implemented in the SWAN model to evaluate its performance in growth curves analysis and field cases.

Analysis and dissemination field observations.

We have developed an interactive website for the dissemination of field data sets to the NOPP teams (and the community at large). The website (www.waveserver.org) includes an interactive Google Earth implementation that allows the user to visually browse the various datasets (see Figure 1). Thus far we have made the following data sets available through this website:

- 1999 ONR Shoaling Waves Experiment (SHOWEX), wave transformation across a wide continental shelf;
- 2003 ONR Nearshore Canyon Experiment (NCEX), refraction over nearshore bathymetry;
- 2004 SAX04, Florida Gulf Coast (ONR Ripples DRI), wave attenuation due to bottom friction;
- 2007 Martha's Vineyard Experiment (ONR Ripples DRI), nearshore wave propagation over inhomogeneous bottom decomposition;
- 2008 ONR Waves-over-Mud MURI (Louisiana), wave propagation over muddy seafloor;
- 2009-2010 High-resolution Air-Sea experiment, drifter observations of coastal wave evolution;

Of particular interest to the NOPP team is the recently added SHOWEX data, which captures wave evolution across the wide shelf of the Mid-Atlantic Bight, in the region between Cape Hatteras and the entrance to the Chesapeake Bay, and includes detailed measurements of hurricane swells (Ardhuin et al., 2003a,b) and fetch-limited wave growth (Ardhuin et al., 2007).

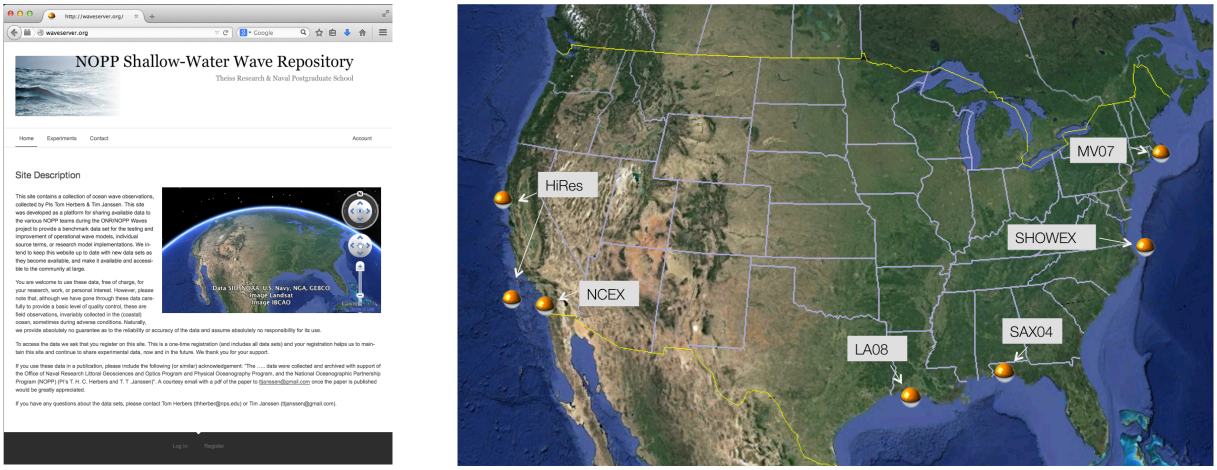

Figure 1 Left panel: Snapshot of www.waveserver.org. This website is developed as part of this NOPP project to disseminate field observations collected by the PIs and colleagues, with the NOPP teams and the community at large. The home page includes an interactive Google Earth window that allows users to browse through the various datasets. A link to the dataset appears when the user clicks on the buoy icon in the panel. The right panel shows a zoom-in of the Google Earth window with labels for each of the experiment sites for which data is available.

Testing of benchmark deterministic models

To develop a benchmark model for further validation of the shallow-water closure approximations developed in this project, we have implemented and tested a non-hydrostatic model (SWASH) to capture nonlinear wave propagation in a dissipative surf zone (see Smit et al. 2014a). Non-hydrostatic models provide an efficient means to model nonlinear wave propagation and the results are very promising (see Figure 2). However, for the sake of efficiency, non-hydrostatic models assume a single-valued free surface in the horizontal plane, such that the effects of overturning (including air entrainment and wave-generated turbulence) are at best very crudely represented. Work to investigate the effects of overturning dynamics on the statistics is ongoing using a Smoothed Particle Hydrodynamics (SPH) model (see e.g. Dalrymple & Rogers, 2006).

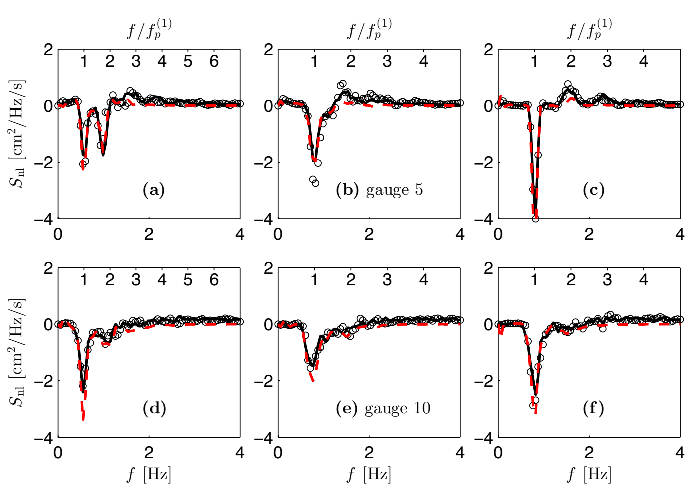

Figure 2 The non-linear source term S_{nl} computed from the bispectrum obtained from the observations (markers) and SWASH model computations (solid black line), and the linear flux gradient (dashed red line) estimated from model results. The lower horizontal axis indicates the frequency, whereas the upper axis in each panel indicates the normalized (by the peak frequency) frequency.

Wave inhomogeneity in stochastic models

Operational wave models are invariably based on some form of the radiative transfer equation (RTE) with source terms added to account for non-conservative and nonlinear effects. This implies that the wave field is assumed near-homogeneous and near-Gaussian so that individual spectral components can be treated as independent. Although generally a reasonable assumption for open ocean applications, over the continental shelves and in coastal waters, inhomogeneous and nonlinear effects can strongly affect wave evolution. Both nonlinearity and inhomogeneity result in the development of cross-correlations between wave components. These cross-correlations contribute to the wave field statistics, but can not be transported by the RTE (which only transports the energy-carrying variance contributions). To obtain a more general model for the transport of wave correlators, we developed a quasi-coherent theory for stochastic waves (see Smit & Janssen, 2013). This is a new modeling paradigm to incorporate wave cross-correlators in stochastic models. We have tested the new theory and implemented it in a research stochastic model suitable for coastal scales. This is an essential step toward developing operational modeling capability for inhomogeneous and non-Gaussian effects near the coast. Work toward a nonlinear extension of the model is ongoing.

Operational model performance tested with drifter observations

We have used recent observations of wave-current interaction in the mouth of the Columbia river to validate the performance of operational wave models (SWAN) in such regions.

RESULTS

Nonlinear statistics of overturning waves

To develop a benchmark to test stochastic closure models, we have tested the performance of a non-hydrostatic model for simulation of nonlinear wave propagation through a dissipative surfzone (see Smit et al. 2014a). Non-hydrostatic models are very efficient but do not capture overturning dynamics in plunging breakers. To develop a deterministic modeling platform for closure validation, which includes overturning waves, we have implemented a Smoothed-Particle Hydrodynamics model (see Dalrymple & Rogers, 2006). The deterministic comparison to laboratory video observations of waves breaking over an artificial reef is excellent (see Figure 3), suggesting that both nonlinearity and dissipation are accurately represented in the model. Longer simulations and Monte-Carlo simulations to obtain reliable statistics of laboratory observations (Boers, 1996) are ongoing.

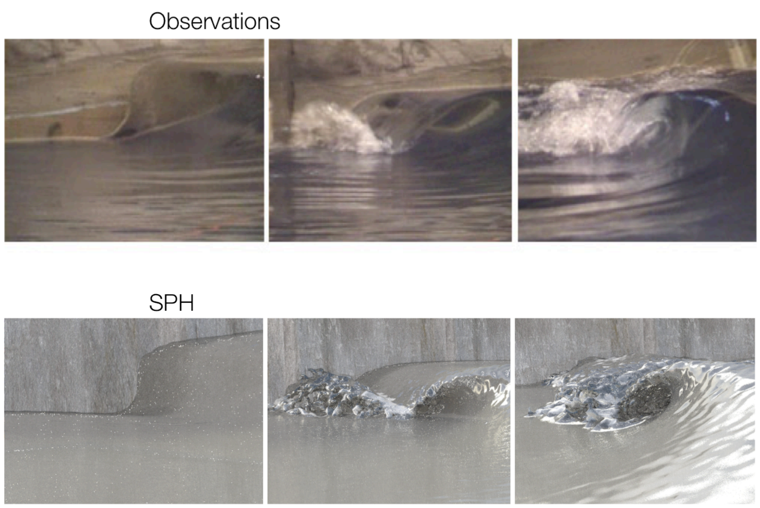

Figure 3 Smoothed-Particle Hydrodynamics (SPH) simulations of waves breaking over an artificial reef in the laboratory (see Henriquez, 2004). Top panel shows three snapshots of the overturning (and breaking) wave over the reef. Bottom panel shows a rendering of the water surface as predicted by the SPH model (see Dalrymple & Rogers, 2006). The agreement in the breaker dynamics predicted by the model and seen in the observations is excellent.

Field data dissemination

The new datasets made available through www.waveserver.org include data from the 2009-2010 High-Resolution Air-Sea interaction DRI, and the 1999 ONR-funded Shoaling Waves Experiment (SHOWEX).

Statistics of coastal wave interference

The quasi-coherent (QC) theory developed by Smit & Janssen (2013) provides a stochastic modeling platform to model coherent interferences due to refraction near the coast. Using the coherent length scale inherent to the wave field, we derived a consistent model that can be written in an RTE-like form as (see Smit et al. 2014b)

$$\partial_t E + c_{\mathbf{x}} \cdot \nabla_{\mathbf{x}} E + c_{\mathbf{k}} \cdot \nabla_{\mathbf{k}} E = S_{\mathrm{QC}} \quad (2)$$

where ∂_t denotes partial differentiation with respect to the subscripted variable, $\nabla_{\mathbf{x}} = \left[\partial_x, \partial_y\right]$ and $\nabla_{\mathbf{k}} = \left[\partial_{k_x}, \partial_{k_y}\right]$. The $c_{\mathbf{x}}$ and $c_{\mathbf{k}}$ represent transport velocities through physical and spectral space respectively. The left side of equation (1.1) is an RTE-like transport equation for the coupled-mode spectrum E, and the right side of (2) represents a source term to incorporate the development of wave

cross-correlations (inhomogeneities) due to medium variations (for details see Smit et al. 2014b). By recasting the QC theory from Smit & Janssen (2013) in the form of (1), the similarities (and differences) with standard RTE-type models are more clear and numerical implementation of QC theory is simplified. Comparison of QC and RTE model simulations to observations of wave evolution during NCEX, shows that in the presence of strong refraction and in regions of coherent interference, QC theory provides a better approximation of the bulk wave statistics (see Figure 4). In addition to improved bulk statistics in regions where coherent interference is important, models based on QC theory can provide more complete statistical information. For instance, in regions of coherent interference, partial standing wave motion occurs in the lateral direction (approximately perpendicular to the mean wave direction of propagation), which affects circulation and transport dynamics. Such information is not available in RTE models (since wave components are assumed independent from the outset). In contrast, a model based on QC theory can produce the complete spatial covariance and thus describe the complete second-order statistics.

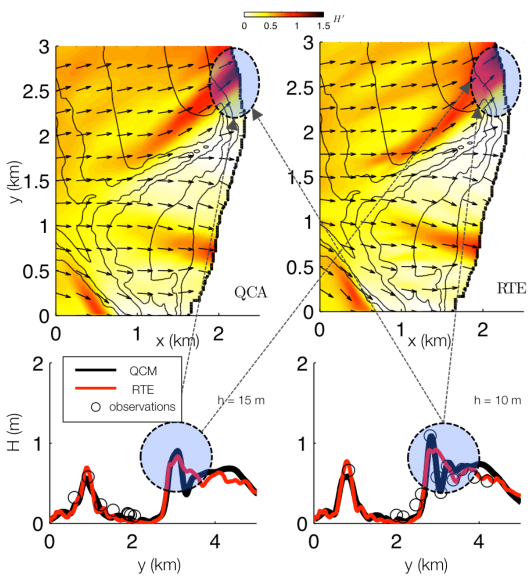

Figure 4 Comparison QC and RTE model simulations to observations of wave evolution across a nearshore canyon as observed during the ONR Nearshore Canyon Experiment (NCEX), in 2003 (see http://waveserver.org/nearshore-canyon-experiment-ncex/). The comparison is for a south swell field with a peak period of approximately 18s, as observed on 16 November 2003 (see Smit et al, 2014b). Top panels show normalized wave heights for QC approximation (left panel) and RTE (right panel). Bottom panels show normalized wave height along 15m (left) and 10m (right) depth contours. In most regions the agreement between observations and models is quite good and comparable. However, near the canyon heads, where coherent effects are important, the wave heights predicted by the QC model are in much better agreement with the observations (where available) than the RTE model predictions.

An example of the spatial covariance function for the same wave field as depicted in Figure 4 is shown in Figure 5, for two different center locations (left and right panel, respectively). This analysis shows that coherent effects are important near the Scripps canyon head where the wave covariance function develops nodal lines roughly parallel to the mean direction of wave propagation, indicative of partially standing wave motion in the lateral direction (see also Smit et al., 2014b). The presence of standing wave motion was confirmed from a cross-correlation analysis of the available field observations (not shown here, see Smit et al, 2014b). The spatial covariance function also shows that just north and south of the Scripps Canyon the wave field remains some correlation despite the complicated refraction and scattering of wave energy across the complex coastal bathymetry.

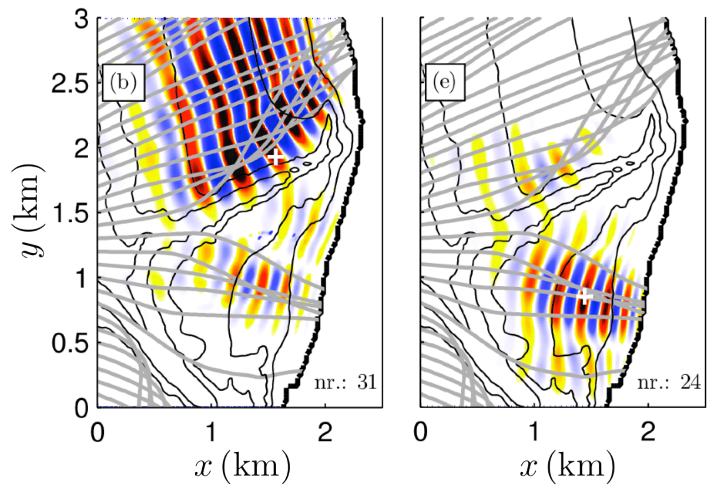

Figure 5 Spatial covariance function of the same wave field as considered in Figure 4. Solid grey lines represent wave rays computed for this wave field. Left panel shows covariance function centered just north of the Scripps canyon head (center location indicated by white cross). Right panel shows covariance function centered roughly midway between La Jolla and Scripps canyon (white cross). From the covariance function centered north of the canyon head (left panel) we see that a nodal pattern spreads out to the north and some correlation exists between waves north and south of the canyon. The covariance function centered between the canyon heads (right panel) is indicative of a fairly homogeneous wave field (for which the RTE would be a reasonable approximation).

The covariance function centered in between the Scripps canyon in the north and La Jolla canyon in the south is quite similar to homogeneous theory (not shown) suggesting that coherent effects are less important in this region. The enhanced capability of QC theory to resolve the covariance function and identify standing wave motion and inhomogeneous effects can help improve coastal circulation and sediment transport models, which rely heavily on a correct representation of wave forcing of the mean flow and are sensitive to spatial variations in wave height, especially if the conditions are close to the threshold for sediment motion.

IMPACT/IMPLICATIONS

The model improvements developed and tested in this study will contribute to improvements in modeling capability of nearshore wave propagation in research and operational models. Efficient and accurate approximations for four-wave interactions will improve prediction of spectral shapes in operational models. The development of general evolution equations for wave correlators form a basis for the development of a new class of stochastic models that include inhomogeneous and non-Gaussian statistics. In turn, improved modeling capability of wave dissipation, spectral evolution, and higher-order statistics such as skewness and asymmetry, will contribute to improvements in research and modeling of coastal circulation and transport processes.

RELATED PROJECTS

The development of transport equations for cross-correlations in random waves also contributes to the study of coastal wave-current interaction as part of the ONR Inlets and River Mouths DRI.

REFERENCES

Ardhuin, F., T. H. C. Herbers, G. Ph. van Vledder, K. P. Watts, R. Jensen, and H. C. Graber, Swell and slanting-fetch effects on wind wave growth, *J. Phys. Oceanogr.*, **37**(4), 908-931, 2007.

Ardhuin, F., T. H. C. Herbers, P. F. Jessen, and W. C. O'Reilly, Swell transformation across the continental shelf. Part II. Validation of a spectral energy balance equation, *J. Phys. Oceanogr.*, **33**(9), 1940-1953, 2003b.

Ardhuin, F., W. C. O'Reilly, T. H. C. Herbers, and P. F. Jessen, Swell transformation across the continental shelf. Part I. Attenuation and directional broadening, *J. Phys. Oceanogr.*, **33**(9), 1921-1939, 2003a.

Boers, M. 1996; Simulation of a surf zone with a barred beach, part 1: Wave heights and wave breaking, *Comm. Hydr. Geotechn. Engn.* 96-5 Delft University of Technology, 116 pp.

Dalrymple, R.A. and B.D. Rogers, 2006; Numerical modeling of water waves with the SPH method, *Coast. Engn.,* **53**, 141-147.

Dungey, J. C., and W.H. Hui, 1979; Nonlinear energy transfer in narrow gravity wave spectrum. *Proc. Roy. Soc. London* **A368**, 239–265.

Gagnaire-Renou, E., M. Benoit, and P. Forget, 2010; Ocean wave spectrum properties as derived from quasi-exact computations of nonlinear wave-wave interactions. *J. Geophys. Res.*, **115**, C12058.

Henriquez, M. , 2004; Artifical Surf Reefs, *MSc Thesis Delft University of Technology*, 53 pp.

Janssen, T. T., T.H.C. Herbers, and J. A. Battjes, 2006; Generalized evolution equations for nonlinear surface gravity waves over two-dimensional topography, *J. Fluid Mech.* **552**, 393-418.

Janssen, T.T. 2006; Nonlinear surface waves over topography, *PhD dissertation*, Delft University of Technology, 208p.

Lavrenov, I.V., 2001; Effect of wind wave parameter fluctuation on the nonlinear spectrum evolution, *J. Phys. Oceanogr.,* **31**, 861–873.

Masuda, A., 1980; Nonlinear energy transfer between wind waves. *J. Phys. Oceanogr.*, **10**, 2082-2093.

Onorato, M., P.A.E.M. Janssen and R. Bidlot, 2013; On the Nonlinear Transfer Calculation. Presentation at the 2013 WISE meeting, Camp Springs, MA, USA.

Smit P. B. and T. T. Janssen, 2013; The evolution of inhomogeneous wave statistics through a variable medium, *J. Phys Ocean.*, **43**, 1741-1758.

Smit P. B., T. T. Janssen, and T.H.C. Herbers, 2014b; Statistics of coastal wave interference. *J. Geophys. Res.* [in review, refereed].

Smit P. B., T. T. Janssen, L. H. Holthuijsen, and J. Smith, 2014a; Non-hydrostatic modeling of surfzone wave dynamics, *Coast Engn.* **83**, 36-48.

Van Vledder, G. Ph., 2006; The WRT method for the computation of non-linear four-wave interactions in discrete spectral wave models. *Coastal Eng.*, **53**, 223–242.

Van Vledder, G.Ph. amd N. Hashimoto, 2013; Inter-comparison study of methods for computing non-linear four-wave interactions in discrete spectral wave models. Proc. 13th Int. Workshop on Wave Hindcasting and Foercasting. Banff, Canada.

Van Vledder, G.Ph., 2001; Extension of the discrete interaction approximation for computing quadruplet wave-wave interactions in operational wave prediction models. *Proc. 4th ASCE Int. Symp. on Ocean Waves, Measurement and Analysis*, San Francisco, CA, USA..

Van Vledder, G.Ph., 2012; Efficient algorithms for non-linear four-wave interactions. *Proc. ECMWF Workshop on Ocean Waves*.

PUBLICATIONS

Engelstad, A., T.T. Janssen, T.H.C. Herbers, G. Ph. Van Vledder, S. Elgar, B. Raubenheimer, L.T. Trainor, and A. Garcia-Garcia, 2012; Wave evolution across the Louisiana shelf, *Cont. Shelf Res.* **52**, 190-202. [published, refereed]

Pearman, D.W., T.H.C. Herbers, T.T. Janssen, H.D. Van Ettinger, S.F.McIntyre, P.F. Jessen, 2014; GPS and accelerometer equipped drifters for observing ocean surface waves and currents, *Cont. Shelf Res.* [in press, refereed]

Rogers, W.C., and G.Ph. van Vledder, 2013; Frequency width in predictions of wind-sea spectra and the role of the nonlinear solver. *Ocean Modeling*, **70**, 52-61 [published, refereed]

Smit P. and T. T. Janssen, 2013; The evolution of inhomogeneous wave statistics through a variable medium, *J. Phys. Ocean.*, **43**, 1741-1758. [published, refereed]

Smit P. B., T. T. Janssen, L. H. Holthuijsen, and J. Smith, 2014a; Non-hydrostatic modeling of surfzone wave dynamics, *Coast Engn.* **83**, 36-48. [published, refereed]

Smit P. B., T. T. Janssen, and T.H.C. Herbers, 2014b; Statistics of coastal wave interference. *J. Geophys. Res.* [in review, refereed].